The reconstruction of jets, missing E_T and boosted heavy particles with ATLAS in Run 2

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Abstract. The reconstruction of jets, missing E_T and boosted heavy particles decaying hadronically has proved to be of extreme importance in Run 1 of the LHC, and has great potential to uncover new physics with Run 2 data. The excellent ATLAS detector capabilities, in particular its high-resolution longitudinally segmented calorimeter and inner detector, have enabled the development of complex clustering and calibration algorithms for the reconstruction of such quantities. In this talk the performance of the tools determined using Run 2 data are presented.

1 Introduction

The ATLAS experiment [1] at the LHC is a multi-purpose particle detector with a forward-backward symmetric cylindrical geometry and a near 4π coverage in solid angle. Studies of the first data collected by ATLAS at center of mass energy $\sqrt{s}=13$ TeV in June-July 2015 allowed to test the performance of the detector. Experimental measurement were compared with the simulated ones. Some results are presented in this talk. Section 2 gives a brief description of the ATLAS detector. The reconstruction and calibration of the jets [2] are discussed in Section 3. Section 4 covers the details of the determination of large distance parameter jet substructure and jet tagging [3]. Finally, Section 5 presents the performance of the missing transverse energy reconstruction [4]. Conclusions are drawn in Section 6.

2 The ATLAS detector

The ATLAS detector [1] consists of an inner tracking detector (ID) residing in a 2 T axial magnetic field provided by a superconducting solenoid, surrounded by electromagnetic and hadronic calorimetry, and a muon spectrometer. The ID covers the pseudo-rapidity range $|\eta| < 2.5$ and consists of a silicon pixel detector, a silicon micro-strip detector (SCT) and a transition radiation tracker (TRT). During the first LHC long shutdown, a new tracking layer, known as the Insertable B-Layer (IBL) [5], was added close to the beam pipe. The high-granularity lead/liquid-argon (LAr) sampling electromagnetic calorimeter covers the region $|\eta| < 3.2$. The iron-scintillator tile calorimeter provides hadronic coverage in the central pseudo-rapidity range $|\eta| < 1.7$. LAr technology is also used for the hadronic calorimeters in the end-cap region $1.5 < |\eta| < 3.2$ and for both electromagnetic and hadronic measurements in the forward region, to $|\eta| < 4.9$. The muon spectrometer (MS) surrounds the calorimeters. It

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consists of three large superconducting air-core toroid magnets, precision tracking chambers providing accurate muon tracking out to $|\eta| = 2.7$ and additional detectors for triggering in the region $|\eta| < 2.4$. A two-level trigger system is used to select events. There is a low-level hardware trigger which reduces the incoming data rate, and a high-level software trigger which selects interesting final state events.

3 Inputs to jet reconstruction and the properties of the jets

The production of energetic jets of particles in p-p collisions is one of the most numerous processes observed at LHC. The measurements allow to check perturbative QCD predictions and to search new physics. The performance of the jet reconstruction was checked using early 2015 data corresponding to an integrated luminosity of approximately 6.4 pb^{-1} [2]. In the analysis the same selection criteria were applied to both the MC simulation and to the data. Jets with transverse momentum $p_T^{\text{jet}} > 25 \text{ GeV}$ were considered.

3.1 Jet reconstruction

The reconstruction of jets requires [6]: a) the finding and calibration of group of calorimeter cells topologically connected (topo-clusters) [7], b) jet clustering of topo-clusters (anti- k_t algorithm [8] with $R = 0.4$) and correction for pile-up, c) MC calibration of the jet vs. pseudo-rapidity and d) residual calibration using in situ measurements.

3.2 Jet reconstruction performance

In general the MC simulation describes the data distributions to within about 10%. The experimental and simulated p_T^{jet} distributions are compared in Fig. 1 (left). In the case of the $\eta_{\text{det}}^{\text{jet}}$ distribution (Figure 1 (right)) the big disagreement between data and MC in the gap region ($1.2 < |\eta| < 1.8$) is due to the miss-calibration of the special scintillation counters. Large differences are observed also in the forward regions ($3.1 < |\eta| < 4.9$). The jet azimuth angle distribution is well modeled [2].

Figure 1. p_T^{jet} distributions (left). $\eta_{\text{det}}^{\text{jet}}$ distributions (right). The relative differences data/MC are shown in the plots [2].

Figure 2 (left) shows the average cluster multiplicity vs. p_T^{jet} . The differences between data and MC are $< 20\%$. As shown in Fig. 2 (right) the average of the fraction of the energy carried by the leading cluster $\langle f_{\text{clus}} \rangle$ vs. p_T^{jet} is well modeled in MC. About 25% of the jet momentum is contained within

a single cluster. The multiplicity and the kinematic distributions of the charged particles associated to jets are also well described in MC [2].

Figure 2. Average cluster multiplicity vs. p_T^{jet} (left). Average of the fraction of the energy carried by the leading cluster vs. p_T^{jet} (right). The relative differences data MC are shown in the plots [2].

The comparison with MC shows reasonable understanding of the longitudinal jet energy profile including the leakage in the muon system. As an example, Fig. 3 (left) shows the energy deposited in the first radial module of the hadronic calorimeter TileCal as a function of p_T^{jet} . The transversal profile of the jet clusters and of the jet associated tracks are generally well modeled. The jets clusters average width vs. p_T^{jet} is shown in Fig 3 (right).

Figure 3. (left) Energy deposited in the first radial module (TileBar0) of the hadronic calorimeter TileCal vs. p_T^{jet} . (right) Jets width vs. p_T^{jet} . The relative differences data MC are shown in the plots [2].

4 Jet substructure performance

Hadronic decays of Lorentz-boosted massive particles are gaining prominence both as useful probes of physics beyond the Standard Model (see for example [9]) and in precision measurements of Standard Model observables. When a boosted heavy particle of mass m and transverse momentum p_T decays,

the average angular separation between the decay products scales with m/p_T . If this angle is small enough, the decay products are reconstructed as a single jet, and jet substructure techniques become a powerful toolkit for discriminating heavy particle decays from continuum multi-jet processes. The performance studies presented in the talk was focused on jets with $p_T^{\text{jet}} > 200$ GeV. The sample of data analyzed corresponds to an integrated luminosity of about 50 pb^{-1} [3].

4.1 Reconstruction of large radius Jets

In ATLAS three different large-radius jet algorithms are considered where the inputs, combination ordering, stopping criterion, and grooming approach vary [4]. One of the three methods is discussed in this talk. Trimmed Jets are built from LCW [6] topological clusters with the anti- k_t algorithm [8] using $R = 1.0$. They are then trimmed [10] using $R_{\text{sub}} = 0.2 k_t$ sub-jets, removing those whose p_T fraction is less than $f_{\text{cut}} = 5\%$ of the jet p_T . The trimmed jet p_T^{jet} is further calibrated to account for the residual detector response [11]. The diagram in Fig. 4 depicts the jet trimming procedure.

Figure 4. Diagram depicting the jet trimming procedure [11].

4.2 Performance of the reconstruction of large radius Jets

Figure 5 (left) shows the large-jet constituent multiplicity distribution after trimming. There are on average fewer clusters in data than in MC, but the level of disagreement is $< 15\%$. The distribution of the number of trimmed jets sub-jets is shown in Fig. 5 (right). The agreement is good for small sub-jet multiplicities, it degrades for values > 3 .

Figure 6 (left) shows the transverse momentum distribution of the trimmed jets. The mass of a jet is given by the difference between the squared sums of the energy E_i and momenta p_i of the constituents. The averages jet mass as a function of p_T^{jet} obtained using experimental and simulated data are shown in Fig. 6 (right). The shape is modeled in MC within 5-10%.

The mass of the jets discussed in the previous subsection can be used for discriminating heavy particle decays from continuum multi-jet processes. To this aim additional substructure quantities were studied in ATLAS [3]. In this talk the N-subjettiness [12, 13] variables, denoted τ_N , were discussed. They attempt to determine the degree to which a given large-radius jet is composed of N or fewer sub-jets. The ratio of the resulting variables is useful in discriminating N from (N-1)-body structures within jets. For instance, two body decay boson jets have smaller values of $\tau_{21} = \tau_2/\tau_1$ than QCD jets. The τ_{21} N-subjettiness ratios distributions obtained using the early 2015 data are reported in Fig. 7. Typical differences of about 10-15% are observed.

Figure 5. (left) Trimmed jet constituent multiplicity. (right) Distribution of the number of the trimmed jets. The ratios data MC are shown in the plots [3].

Figure 6. (left) Trimmed jets p_T^{jet} distribution. (right) Average jet mass as a function of the jet transverse momentum p_T^{jet} . The ratios data MC are shown in the plots [3].

Figure 7. τ_{12} N-subjettiness ratio distributions. The ratios data MC are shown in the plot [3].

5 Missing transverse momentum reconstruction

The missing transverse momentum reconstruction is indicative of weakly interacting stable particles in the final state. The results presented in the talk were obtained analyzing $Z \rightarrow \mu^+ \mu^-$ decay events. The analyzed sample corresponds to an integrated luminosity of approximately 6.4 pb^{-1} [4].

5.1 Missing E_T reconstruction

Using the Track-based Soft Term method [4], the missing transverse momentum components are obtained using the measured $x(y)$ component of the momentum of all the reconstructed physics objects like jets $E_{x(y)}^{\text{jet}}$, electrons $E_{x(y)}^e$, photons $E_{x(y)}^\gamma$, taus $E_{x(y)}^\tau$ and muons $E_{x(y)}^\mu$. The soft term, $E_{x(y)}^{\text{soft}}$, in Eq.(1) does not include contributions from neutral particles and corresponds to the sum of the components of the momentum of all tracks associated with the primary vertex but not matching to any physics object:

$$E_{x(y)}^{\text{miss}} = -(E_{x(y)}^{\text{jet}} + E_{x(y)}^e + E_{x(y)}^\gamma + E_{x(y)}^\tau + E_{x(y)}^\mu + E_{x(y)}^{\text{soft}}) \quad (1)$$

One obtains:

$$E_T^{\text{miss}} = \sqrt{E_x^{\text{miss}} + E_y^{\text{miss}}} \quad (2)$$

The reconstructed missing energy is relatively insensitive to pile-up effects but does not include contributions from neutral particles.

Figure 8. Comparison of the experimental and simulated distributions of E_x^{miss} (left) and E_T^{miss} (right). The ratios data/MC are shown in the plots [4].

5.2 Missing E_T reconstruction performance

The agreement in the bulk of the experimental and simulated distributions is within 20%. As an example the E_x^{miss} and the E_T^{miss} distributions are shown in Fig. 8.

In $Z \rightarrow \mu^+\mu^-$ events neutrinos are produced only through heavy flavour meson decays, so this channel has very little genuine missing energy and the RMS of the E_T^{miss} distributions is indicative of the measurement resolution. Figure 9 (left) shows the resolution of the $E_{x(y)}^{\text{miss}}$ distributions as a function of the number of primary vertices. A bin is required to have a minimum of 200 events to be considered for the resolution curve. Good agreement is found between experimental and simulated data results.

In $Z \rightarrow \mu^+\mu^-$ events the mean value of E_T^{miss} projected onto the unit vector A_Z parallel to momentum of the Z particle, p_T^Z , is a measure of the E_T^{miss} scale. The negative bias of about 5 GeV observed

Figure 9. (left) Resolution of the $E_{x(y)}^{\text{miss}}$ determinations as a function of the number of primary vertices. (right) Mean value of the projection of E_T^{miss} along the Z particle transverse momentum, p_T^Z , as a function p_T^Z . A bin is required to have a minimum of 200 events to be considered for the plots [4].

in data and MC (see Fig. 9 (right)) indicates an underestimation of the E_T^{miss} determination due to a) soft neutral particles and b) limited acceptance of the Inner Detector (ID). A bin is required to have a minimum of 200 events to be considered for the scale plot.

6 Conclusions

ATLAS performance concerning the reconstruction of jet reconstruction, the determination of the structures of large radius jets and the missing transverse energy determination has been studied and compared to MC results using first 13 TeV collision data collected in 2015. Reasonable agreement between data and MC simulation is observed.

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